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Morphological and sedimentological responses of streams to human impact in the southern Blue Ridge Mountains, USA

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Abstract

Morphological and sedimentological responses of streams to basin-scale impact have been well documented for intensively agricultural or urban areas. Sensitivity thresholds of streams to modest levels of disturbance, however, are not well understood. This study addresses the influence of forest conversion on streams of the southern Blue Ridge Mountains, a region that has received little attention with respect to human impact on stream channels. Basins were chosen for this study to represent the end members of the range of human impact in the area, with the forest cover of the basin used as a proxy for level of impact (ranging from about 70–100% regionally). Two pairs of lightly impacted (>90% forest) and moderately impacted (70–80% forest) sub-basins of the upper Little Tennessee River were identified for comparison. Reach characteristics (e.g., slope, drainage area, and riparian cover) were aligned in each pair to isolate contrasting forest cover as the primary driver of any detected differences in morphology and sedimentology. A suite of standard cross-sectional and longitudinal data was collected for each reach for characterization of the sedimentology and morphology of the streams. Difference of means tests were conducted to identify parameters significantly differing between the lightly and moderately impacted streams in both pairs. Consistent and significant differences within both pairs were demonstrated in bankfull width/depth ratios, baseflow wetted width, and particle size on the stream bed both in the thalweg and throughout the channel bed. The moderately impacted streams are narrower than the lightly impacted streams, and the bed texture of the moderately impacted streams is finer than that of the lightly impacted streams. The moderately impacted streams contain a higher percentage of <2 mm particles in riffles, a metric which has been shown to be highly correlated with biotic integrity in the southern Appalachian Highlands. Although this study has shown that human impact in these basins has resulted in an overall fining of bed texture, few conclusions can be drawn regarding the morphological response of the streams to the levels of impact affecting the upper Little Tennessee River basin. Levels of disturbance in the southern Blue Ridge Mountains may be below the thresholds of morphological sensitivity or have not persisted for sufficient duration for morphological response to be evident. Additionally, morphological adjustment to disturbance may be more effectively addressed system-wide, as opposed to at the reach scale.
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Keywords: Mountain stream; Appalachians; Land use; Deforestation; Sediment

1. Introduction

This study considers the effects of forest clearance on streams of the southern Blue Ridge Mountains, a region that has received little attention with respect to human impact on stream channels. This region facilitates

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analysis of the response of streams to relatively modest levels of deforestation, as opposed to the widespread and complete conversion of native forests to agricultural or urban landscapes that has been the predominant focus of prior research. The primary objective of this study was to assess whether the morphology and sedimentology of streams respond to moderate basin-scale impact (forest conversion) in the southern Blue Ridge. The secondary objective was to identify which morphological and sedimentological parameters, if any, may serve as indicators of disturbance in this region. We sought to characterize the morphology and sedimentology of streams in the southern Blue Ridge that have experienced contrasting levels of basin-scale impact by selecting pairs of the most- and least-forested basins in the region for comparison.

2. Background: highland streams

Because of lower population densities, human impacts on mountain streams often differ from those related to intensive agriculture or urbanization, which have been thoroughly studied (e.g., Wolman, 1967; Trimble, 1981; Knox, 1987; Brooks and Brierley, 1997; Doyle et al., 2000). Development pressures are typically lower in mountainous regions than in lower-relief areas, in part because of the difficulty of access and higher likelihood of landscape protection on public lands. Human impacts in high relief areas include timber harvest, road building, grazing, and limited agriculture (Wohl, 2000). Additionally, many highland regions have begun to face a significant growth of population and exurban second-home development in recent years. Though the nature and extent of impact may differ from low-relief areas, the responses of streams to human activity in mountain basins, like responses to impact in lowlands, are largely a product of adjustments in prevailing fluxes of water and/or sediment. Many mountain stream systems are particularly sensitive to external influences, as small to moderate changes in stream discharge or sediment supply can alter stream sedimentology and morphology; this is especially true for pool-riffle reaches of mountain streams (Montgomery and Buffington, 1997).

Timber harvest and associated road building are among the most-studied and highest-impact human activities in high relief regions (Wohl, 2000). Exposure of soil from the removal of forest increases susceptibility to surface erosion of slopes (Johnson and Beschta, 1980). Additionally, timber harvest is generally accompanied by reduced interception and infiltration, thereby increasing overland flow and soil erosion. Jackson et al. (2001) demonstrated lower median sizes of bed particles in non-riparian buffered streams following clearcut harvest than in reference streams. The fining of bed sediments was linked with population decline of some amphibian species. Increases in channel capacity have been demonstrated in association with higher peak flows because of the removal of forest in mountain basins in the Pacific Northwest (Heede, 1991; Hartman et al., 1996). Wood-Smith and Buffington (1996) found differences in the distribution of habitat units in channels between pristine streams and those impacted primarily by timber harvest and road building in southeastern Alaska. Road construction is associated with the destabilization of slopes and increased yield of sediment (Reid and Dunne, 1984; Sah and Mazari, 1998), and can intensify the impacts of timber harvest on highland streams. The density of roads and related sources of sediment were found to account for 51% of the sediment loading of impaired southern Blue Ridge streams (Pruitt et al., 2001).

The above examples illustrate the susceptibility of mountain streams to the clearance of forests and related activities, but the specific response of streams in the Blue Ridge Mountains is not well understood. More importantly, the nature of current human impact in this region differs significantly from the large scale timber harvest that has been the focus of abundant research in the western United States. A clearer understanding of the response of streams to long-term conversion of forests resulting from population expansion into highland regions needs to be gained. The pressures of development that many mountainous regions throughout the world are currently facing are not necessarily characterized by the intense, intermittent processes typical of timber harvest. Instead, land cover and land use changes are more varied and gradual, but persist for extended periods of time, thus allowing little to no opportunity for stream systems to recover. The vast archive of research on timber harvest has allowed the development of best management practices (BMP) that provide guidelines to minimize the impacts of timber harvest on stream systems (Aust, 1994; Prud'homme and Greis, 2002; Fortino et al., 2004; Wang et al., 2004). Nothing of the sort exists for the forest conversion that accompanies general population growth in sensitive highland regions, which is increasingly pressuring stream ecosystems and water resources throughout the world.

3. Study area

Four tributary streams to the upper Little Tennessee River, comprising two pairs with contrasting levels of deforestation, were selected for study. The upper Little Tennessee River drains part of the southern Blue Ridge physiographic province of northeast Georgia and western North Carolina (Fig. 1). In the absence of human land use, this region would be very nearly 100% forested (Yarnell, 1998), and classification of Landsat™ imagery indicates that the upper Little Tennessee River basin was approximately 82% forested in 1998 (Table 1). Evidence suggests that the earliest human impact in this region dates to the Late Archaic period (ca. 3000 years ago), when the upper Little Tennessee River basin experienced limited amounts of forest clearance and subsistence crop cultivation by Native Americans (Delcourt et al., 1986; Delcourt and Delcourt, 2004). Extensive timber harvest occurred in the basin by the 1880s (Ayers and Ashe, 1904), and federal acquisition of Appalachian land for the establishment of protected national forests began in 1911 (Walker, 1991; Yarnell, 1998). Human disturbance on private land persists in the form of forest clearance, agriculture, urbanization, road construction, and exurban development of second homes. A substantial portion of the basin, however, is located in the Nantahala and Chattahoochee National Forests, where development and timber harvest have been restricted since the 1930s. The presence of protected and unprotected smaller basins within the upper Little Tennessee drainage provides a unique opportunity to assess the response of streams to modest levels of human impact in the southern Blue Ridge. Most of this region has historically experienced episodic, short-lived disturbance (forest clearing), punctuated by periods of reforestation and potential recovery. Many areas within the unprotected, private land portion of the upper Little Tennessee River basin are facing rapid development and low- to medium-density urbanization pressures that lower relief areas like the adjacent Piedmont have been experiencing for several decades to centuries. This allows for assessment of human impact

Table 1
Upper little Tennessee river basin land cover

Class	Area (km^2)	% of basin
Water	6.91	0.59
Forest	961.89	82.15
Non-forest vegetated	37.59	3.21
Low density urban	27.75	2.37
Medium density urban	6.67	0.57
High density urban	0.00	0.00
Other	127.63	10.90
Total	1168.43	

Classification of 1998 Landsat™ image provided by Barrie Collins, The University of Georgia, Institute of Ecology.

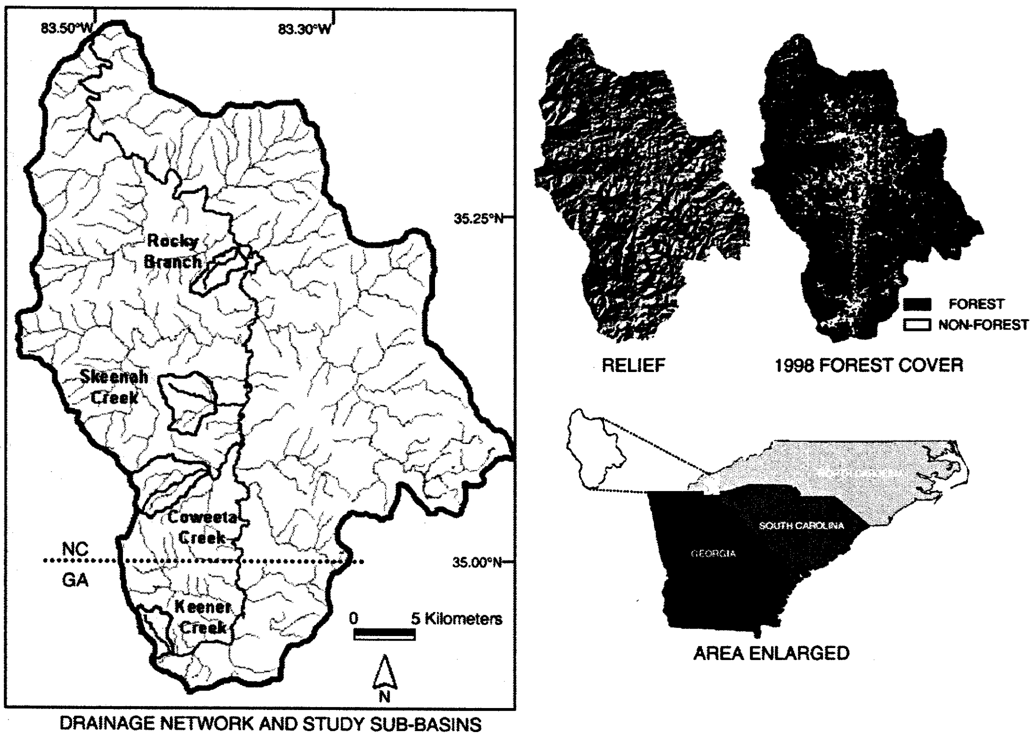

Fig. 1. Study area: upper Little Tennessee River basin. Drainage area = 1164 km^2. In the drainage network, heavier lines indicate the trunk streams of the study sites and the main stem of the Little Tennessee River. Vertical exaggeration of relief = 3×. 1998 basin forest cover = 82%.

on streams at a stage of disturbance that has long passed in many regions.

The bedrock of the upper Little Tennessee River basin is primarily quartz dioritic gneiss and biotite gneiss (Daniel and Payne, 1990; Robinson et al., 1992) covered by a mantle of saprolite and colluvium 1–30 m thick (Hadley and Goldsmith, 1963; Southworth et al., 2003). The landscape has been highly dissected by fluvial processes and mass movements. Eaton et al. (2003) indicate a 2500-year recurrence frequency for debris flows in small Virginia Blue Ridge watersheds. The upper Little Tennessee River flows due north and is fed predominantly by east- and west-flowing tributaries (Fig. 1). The 30-year average annual precipitation at the low elevation gage, operated by the U.S. Forest Service at the Coweeta Experiment Station in the central portion of the basin, is 183 cm, with a high monthly average of 20 cm occurring in March (NCDC, 2003). The 30-year average annual temperature is 12.7 °C, with average January and July temperatures of 2.7 °C and 22.1 °C, respectively (NCDC, 2003). Specific study sites are located in Macon County, North Carolina, and Rabun County, Georgia (Fig. 1).

4. Methods

Basins currently experiencing the regional extremes of development were used to identify differences between the least-impacted and most heavily impacted tributaries of the upper Little Tennessee River. Basin forest coverage has been demonstrated as a useful predictor of stream habitat and biota (Kennan and Ayers, 2002; Leigh et al., 2002; Roy et al., 2003a,b; Walters et al., 2003a,b), and is used herein as a proxy for human impact in the southern Blue Ridge. Many government agencies utilize stream assessments at the reach-scale for characterization of the morphological and sedimentological condition of the stream, e.g., U.S. EPA Environmental Monitoring and Assessment Protocol (EMAP; Kaufmann and Robison, 1998) and USGS National Water Quality Assessment Program (NAWQA; Fitzpatrick et al., 1998). A reach-scale approach was used in this study.

4.1. Site selection

Two pairs of lightly and moderately impacted basins were chosen for comparison on the basis of percentage of forested land in the drainage basins (Fig. 2; see Table 2 for basin attributes). Study reaches were located at the outlets of the basins. Efforts were made to best represent the end members of the range of recent forest cover (70–100%) in tributaries of the upper Little Tennessee River. The percentage of non-forested land was treated as an estimator of the percentage of land experiencing

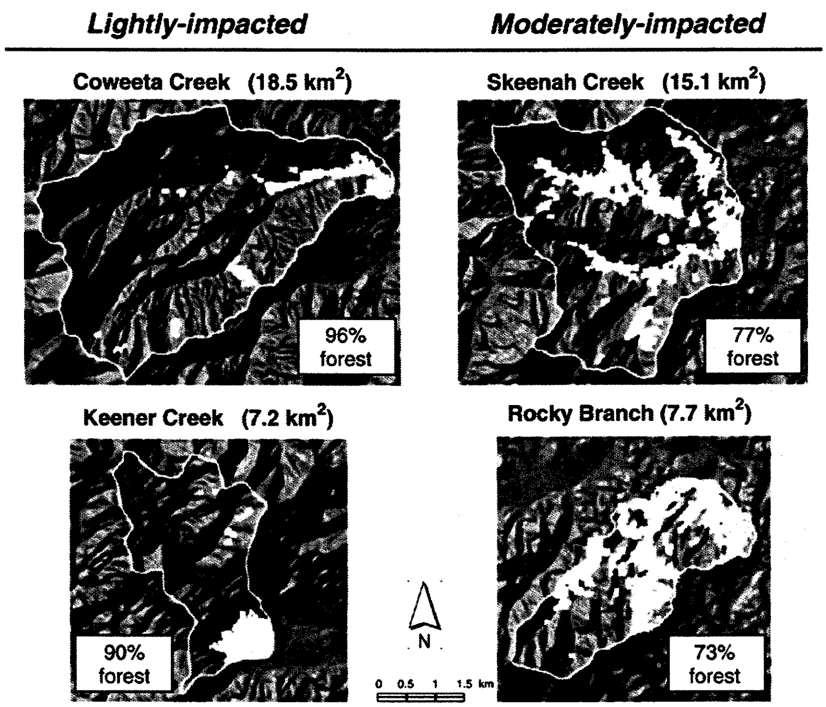

Fig. 2. Study basins. White areas represent non-forest land cover (shown only within delineated study basin). Vertical exaggeration of relief=3×.

Table 2
Basin attributes

		Coweeta (L)	Skeenah (M)	Keener (L)	Rocky (M)
Drainage area (km^2)		18.46	15.07	7.25	7.66
1998 basin land cover (% of total area)	Forest	95.7	77.2	90.0	72.9
	Non-forest vegetated	0.61	2.88	6.08	4.14
	Low density urban	0.36	3.5	0.23	6.47
	Medium density urban	0.01	0.19	0.09	0.38
	High density urban	0	0	0	0
	Water	0.09	0.55	0.01	0.57
	Other	3.22	15.1	3.88	19.07
1950 basin forest cover (% of total area)		94.9	62.9	92.0	66.9
Road coverage (% of basin area)	Total	5.10	4.02	0.86	3.34
	Paved	0.14	0.82	0.29	0.98
	Unpaved	4.96	3.20	0.57	2.36
Road density (km/km^2)	Total	6.61	6.45	1.15	7.50
	Paved	0.16	0.90	0.38	1.25
	Unpaved	6.45	5.55	0.77	6.25
Road/stream crossings	Total	30	36	5	15
	Paved	3	29	2	6
	Unpaved	27	7	3	9
Stream order[a]		3	3	2	2
Trunk stream relief (m)		726	250	381	197
Drainage density (km/km^2)		0.95	0.80	0.57	0.64

L = lightly impacted; M = moderately impacted.
[a] Strahler (1952).

human impact, which includes roads, pasture, cropland, and residential/low density urbanized areas. The selection of lightly and moderately impacted basins was based on analysis of historical state and federal sources for land cover data available for the 1950s, 1970s, 1990 and 1998. Forest cover in the basins was measured using ArcView® 3.2 and Erdas Imagine® software for each year of available data for land cover derived from Landsat™ imagery and aerial photographs. The 1998 forest cover of the lightly impacted basins ranges from 90.0% to 95.7%, and the moderately impacted basins range from 72.9% to 77.2% forested. Road density and coverage, as additional indicators of the level of human impact, were estimated from 1995–1996 images from the National Aerial Photography Program (NAPP) (Table 2). None of the basins contain significant areas of virgin forest. The more forested basins have not been significantly altered since the 1930s. The basins were grouped into the following pairs on the basis of drainage area: (1) 7–8 km^2 and (2) 15–18 km^2. ArcView® software and USGS 7.5-min DRGs were used for the delineation of the drainage basin and calculation of the drainage area.

To isolate human impacts from natural variation, stream study reaches (40 times average wetted width, according to U.S. EPA protocol; Kaufmann and Robison, 1998) with similar hydrologic and physical characteristics were established within each pair (Table 3), as described below. We chose attributes for alignment within pairs based on well-documented linkages to channel morphology and sedimentology. This allowed for evaluation of the role of contrasting basin land use in triggering morphological and sedimentological responses. Flood discharge and gradient are controlling factors in the ability of a stream to erode and transport sediment (Schumm, 1977; Knighton, 1998). For the purposes of site selection, drainage area was used as a proxy for flood discharge (Dunne and Leopold, 1978; Pope et al., 2001). Streams were chosen to have comparable reach slopes within each pair. Reach gradient was measured using a Topcon® total station and standard survey techniques. Total basin relief within each pair is comparable, and all four watersheds have an east-facing aspect. The bedrock geology exhibits consistent hydrogeologic properties across the four basins (Daniel and Payne, 1990). "Pool-riffle" channel morphology characterizes all four streams under the Montgomery and Buffington (1997) classification scheme. Reaches with comparable riparian vegetation cover (9–12%) within a 10-m buffer of the streams within each pair were chosen, to avoid complications from varying riparian condition in interpreting stream differences (Table 3). The conditions of riparian vegetation were estimated from 1995–1996 NAPP

Table 3
Reach attributes

		Coweeta (L)	Skeenah (M)	Keener (L)	Rocky (M)
Reach base (0×) coordinates	e	280,414	281,849	277,332	282,540
(UTM, NAD 83)	n	3,882,480	3,887,962	3,868,128	3,900,283
Riparian vegetation cover (%)		12	11	11	9
Sinuosity		1.07	1.21	1.02	1.08
Average baseflow discharge[a] (m^3/s)		0.55	0.32	0.21	0.12
Near bankfull discharge (m^3/s)		2.66	3.23	1.90	0.79
Estimated bankfull discharge (m^3/s)		4.95	4.12	2.84	1.04
Average baseflow water width[b] (m)		6.35	4.82	3.27	1.97
Average bankfull width[b] (m)		7.58	6.88	4.76	2.42
Average bankfull thalweg depth[b] (m)		0.91	1.36	1.17	0.6
Map slope		0.0050	0.0076	0.0065	0.0045
40× USEPA slope (regression)		0.0106	0.0056	0.0055	0.0060
20× USGS slope (regression)		0.0118	0.0059	0.0052	0.0068
Riffle top slope		0.0108	0.0053	0.0052	0.0068
Average meander belt width[b] (m)		34.55	11.57	5.95	8.75
Meander belt width/channel width		4.86	1.84	1.30	3.92
Terraced banks (of 32)		3	18	22	2
Terraced transects (of 16)		0	3	7	0
% pool	Area	7.03	11.62	1.25	3.30
	Points[c]	7.40	14.81	4.93	2.46
% glide	Area	45.83	63.35	65.99	74.83
	Points[c]	43.21	59.26	50.62	74.07
% riffle	Area	34.86	20.36	32.75	21.87
	Points[c]	43.21	24.69	44.44	23.46
% rapids	Area	12.28	4.67	0.00	0.00
	Points[c]	6.17	1.23	0.00	0.00
Average particle size		very coarse gravel (ϕ=−5 to −6)	medium gravel (ϕ=−3 to −4)	coarse gravel (ϕ=−4 to −5)	fine gravel (ϕ=−2 to −3)
% fines (particles <2 mm)	Channel bed[d]	18.5	35.8	14.8	18.5
	Channel bed[e]	21.0	33.3	21.0	14.8
	Thalweg[d]	1.2	4.0	3.7	3.7
	Riffles[e]	5.0	25.0	7.0	31.0

L=lightly impacted; M=moderately impacted.
[a] n=3 per stream.
[b] n=16 per stream.
[c] n=81 per stream.
[d] Particle size was determined using the dominant phi method (Section 4.2.2).
[e] Particle size determined using individual particle measurement (Section 4.2.4).

images. The study reaches do not contain areas of direct livestock access to the stream. Based on the blue-line stream network on USGS 7.5-min DRGs, the pair of smaller basins (7–8 km^2) is comprised of second-order streams (Strahler, 1952), whereas the larger basins (15–18 km^2) are third-order streams. The smaller pair (2–3 m average width) consists of Keener Creek (lightly impacted) and Rocky Branch (moderately impacted), and the larger pair (4–6 m average width) consists of Coweeta Creek (lightly impacted) and Skeenah Creek (moderately impacted). The nature of the non-forest land cover does not drastically differ among the study basins, with the predominant human land uses classifying as non-forest vegetated (e.g., pasture) or residential/low density urban.

4.2. Collection of field data

Procedures were followed at each stream (according to the spatial sampling design shown in Fig. 3), to measure the variables explained in Table 4. Many of these variables have been shown to exert strong influence on the habitat of a stream and the related biotic integrity of fishes and macroinvertebrates (Roy et al., 2003a,b; Walters et al., 2003a,b).

4.2.1. Establishment of study reach

The average wetted width of the reach was determined, rounded to the nearest meter, and the length of the study reach was designated as 40 times (40×) average width. Beginning at the randomly determined

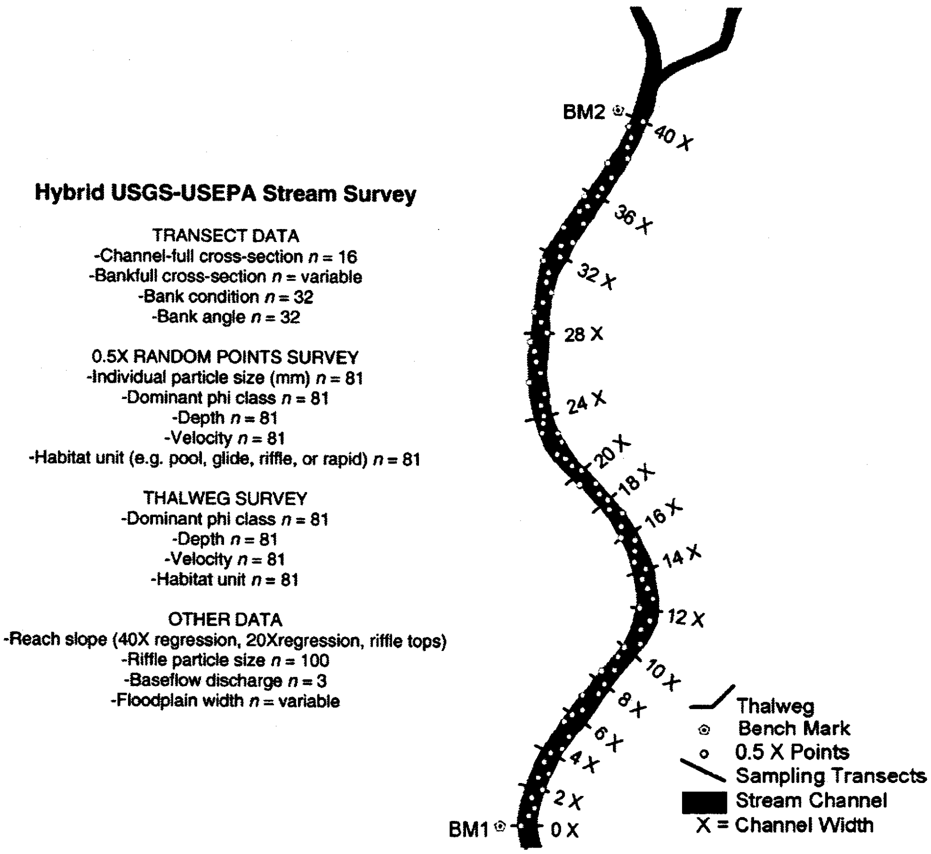

Fig. 3. Sampling design. A combination of USGS (Fitzpatrick et al., 1998) and U.S. EPA (Kaufmann and Robison, 1998) methods for stream assessment was used.

base of each reach (0×), 11 transects were placed perpendicular to the channel at equal intervals of two times channel width, ending with 20 times channel width (20×), according to USGS-NAWQA methods for characterization of stream habitat (Fitzpatrick et al., 1998). An additional five transects were placed at equal intervals of four times channel width beyond the 20× transect, concluding with 40×, thereby satisfying U.S. EPA-EMAP protocol (Kaufmann and Robison, 1998).

4.2.2. Stratigraphic setting

A topographic survey of a transect that extended at least 35 m on either side of the stream was conducted at a representative location for each stream. Each of these extended transects was surveyed using an electronic total station. A Giddings® hydraulic coring rig was used to extract 7.5 cm diameter cores from key landforms (e.g., terraces, floodplains) along the extended transect. Soil cores were described according to USDA terminology (Soil Survey Division Staff, 1993). Fortuitous occurrences of charcoal and uncarbonized organic samples were removed for radiocarbon dating by the University of Georgia Center for Applied Isotope Studies. Radiocarbon dates (δ^{13}C corrected) were calibrated to calendar year age ranges (2σ) using the program Calib Rev 4.4.2 (Stuiver and Reimer, 1993). Soil descriptions were used to generate stratigraphic cross-sections.

4.2.3. Channel morphology

Dimensions of the channels were measured at each transect. The height of the channel was defined by the lowest prominent alluvial surface characterized by vertical accretion facies (Williams, 1978) and noted as either a floodplain or a terrace for each side of the stream. Width of the channel was measured at the level of the top of the bank from the lowest alluvial surface, which was the floodplain in most cases. Measurements of channel dimensions were summarized using two separate approaches: (1) descriptive statistics were generated for all 16 transects per stream (hereafter referred to as "channel-full" dimensions), and (2) summary values were generated for those transects with active floodplain on either or both sides (hereafter

Table 4
Explanation of parameters

Road Coverage: Road length × Road width (measured from 1995–1996 NAPP images), expressed as a % of total basin area
Road Density: Road length (measured from 1995–1996 NAPP images)/total basin area
Road Crossings: Tallied from overlay of blue-line stream network and road network (defined from 1995–1996 NAPP images)
Trunk Stream Relief: Elevation between the basin divide (above the terminus of the map blue-line of trunk stream) and 0×
Drainage Density: Stream length (total blue-line length on USGS DRGs)/total basin area
Map Slope: Elevation/distance of stream derived from USGS DRG countours
40× Slope: Regressed from surveyed cross-sections along 40× reach
20× Slope: Regressed from surveyed cross-sections along 20× reach
Riffle Top Slope: Elevation/distance of stream between surveyed cross-sections transecting riffles near 0× and 40×
Riparian Cover: Woody vegetation cover as % of total area within a 10 m buffer 500 m upstream from 0× (measured from 1995–1996 NAPP images)
Sinuosity: Stream length/valley length (measured from 1995–1996 NAPP images)
Discharge: Calculated from 0.6-depth velocity, water depth, and horizontal channel distance at ≥ 10 points along a transect
Bankfull Width: measured from lowest floodplain surface
Bankfull Depth: measured from lowest floodplain surface to (a) bottom of thalweg and (b) water surface
Channel-full Width: measured from lowest prominent vertical accretion facies (floodplain or terrace)
Channel-full Depth: measured from lowest prominent accretion facies to (a) bottom of thalweg, and (b) water surface
Habitat Coverage—% Area: Habitat units were mapped by field measurement; coverage was computed in ArcView®
Habitat Coverage—% Points: Random survey points were sorted by habitat unit, and % of total observations was calculated
Bank Height: Height from bottom of thalweg to top of lowest prominent vertical accretion facies
Bank Angle: Overall bank angle (measured with a Brunton compass)
Bank Stability Index: Computed from bank height, angle, texture, vegetation cover, and amount of erosion (Fitzpatrick et al., 1998)
Froude Number: Velocity (m/s)/√ (gravitational constant × depth (m))
Dominant Φ: Particle size class (whole phi interval) comprising modal % of surface area within a 50-cm radius of sample point
Individual Particle Measurements (mm): Intermediate axis diameter of a randomly selected particle at each sample point
% Particles < 2 mm: Percent of particles < 2 mm or > −0.5Φ was determined for each particle size parameter
Riffle Fraction: Particle size measurements from sample points in riffles were culled from total column (random and thalweg surveys) and summarized
Meander Belt Width: Floodplain width + channel-full width
Meander Belt/Channel Ratio: (floodplain width + channel-full width)/channel width; used to standardize meander belt width by stream size

referred to as "bankfull" dimensions). The left and right edges of the baseflow water surface were surveyed using a total station. Bank angles, textures, vegetation, and conditions along the 40× reach were described according to the USGS protocol at each of the 16 transects, and these data were used to calculate a bank stability index (Fitzpatrick et al., 1998). Cross-sections of the wetted channel were measured with a steel tape and stadia rod at points situated in the thalweg and at 0, 25%, 50%, 75%, and 100% of water width. Water depth, velocity, and channel habitat unit were recorded at each of these points. Classification of channel units (e.g., rapids, riffles, glides, pools) was based on U.S. EPA categories (Kaufmann and Robison, 1998). Velocity was measured using a Marsh-McBirney Flowmate™ electromagnetic flow meter at 60% of water depth (0.6 depth).

A longitudinal profile of the thalweg was sampled along the entire length of each stream reach according to U.S. EPA protocol (Kaufmann and Robison, 1998). Thalweg samples included water depth, velocity (0.6 depth), and observations of the habitat for channel units at 81 equally spaced points at intervals of one-half the average channel width (0.5×). In addition to the thalweg survey, a sample was drawn from a point selected at a random percentage of stream width at each of the 81 equally spaced distances along the 40× reach. Water depth, velocity, and channel unit were recorded at each random point. The habitat coverage of each channel unit was hand mapped using the U.S. EPA habitat classification scheme (Kaufmann and Robison, 1998). These units were digitized using ArcView® 3.2 software, and percentage of total surface area for each type of habitat was calculated.

Floodplain dimensions and width of the meander belt were measured at each of the 16 cross-sections per stream. To compare the development of meander belts among streams of varied width, we calculated a ratio of the width of the meander belt divided by width of the wetted channel at baseflow for each stream.

4.2.4. Sedimentology

The intermediate axis of a randomly selected particle was measured at each of the 81 random points per stream (hereafter referred to as "individual particle measurements"). In addition, the dominant whole phi size class (phi = $-\log_2$ diameter in mm) was visually assessed for the bed material within a 50-cm radius of the 81 points of the thalweg survey and the 81 random points, to indicate the dominant clast size (hereafter referred to as "dominant phi (Φ)"). A standard Wolman (1954) pebble count on 100 points within a representative riffle in each 40× reach was conducted to measure riffle particle size. From these 100 points, riffle embeddedness was calculated as the fraction smaller than 2 mm. Additionally, the individual particle measurements from the random points survey were sorted by habitat unit, and the mean riffle particle size was determined for each stream along with the percent of particles smaller than 2 mm. Although bulk sampling of riffles to a depth of 10–20 cm has been indicated as a more accurate assessment of available habitat than surface point counts, to date no simultaneously accurate and practical method for bulk sampling of cobble bed streams has been demonstrated (Wohl, 2000; Kondolf et al., 2003).

4.2.5. Discharge

Baseflow discharge was measured at an optimal transect across each stream on three occasions (10 October 2003, 19 January 2004, and 5 February 2004). Measurements of flow were limited to frontal, widespread precipitation events in fall/winter months to avoid potential complications arising from the highly localized summer precipitation characteristic of this region. For this study, conditions were considered baseflow provided the basin had experienced no runoff-generating precipitation over the preceding 72 h. This arbitrary designation was based on observation of streams of similar size throughout the region, to ensure that no surface runoff was included in the measured streamflow. In addition to the collection of baseflow data, flood discharge was measured during a near-bankfull event on 6 February 2004, which affected all four stream basins. The measurements of discharge of all four streams were collected within a 6 h period on each of the four sampling days. Discharge was calculated from cross-sectional dimensions and velocity measurements at 0.6 depth taken over at least 10 intervals of stream width. Bankfull discharge at floodplain height was estimated using surveyed cross-sectional dimensions and the Manning equation, with Manning's "n" derived from the 6 February 2004, near-bankfull measured discharge.

4.3. Statistical analysis

Descriptive statistics of each parameter were generated for each stream. Individual particle measurements in the channel bed survey and the riffle pebble counts were converted to Φ units, and statistics were computed for both metrics. If the means of individual parameters showed a consistent direction of difference between the lightly and moderately impacted streams in both pairs (e.g., for a given parameter, the means of the lightly impacted streams were either both lower or both higher than the moderately impacted counterpart), then statistical difference of means tests were conducted. In preparation for difference of means tests, data columns were checked for normality using the Kolgorov-Smirnov test. When possible, the parameters for which one or more streams were non-normally distributed were normalized using standard transformations ($\log_{10}$, natural log, reciprocal, or square root). Parametric t-tests were run for the normalized variables between the lightly and moderately impacted streams in each pair. For variables that failed to normalize when transformed, Mann-Whitney Rank-Sum non-parametric difference of means tests (to generate "T" values) were run between the lightly and moderately impacted streams in each pair. A threshold probability value (p) of 0.01 was used to define statistically significant differences.

5. Results

This summary emphasizes parameters that showed consistent, statistically significant differences in both stream pairs. One objective of this study was to identify indicators of basin-scale disturbance; however, parameters for which opposite relationships were observed between the lightly and moderately impacted streams will not be addressed. The lightly and moderately impacted streams in this study exhibited significant differences in baseflow wetted width, bankfull width/depth (to thalweg) ratio, dominant particle size in the thalweg and entire channel bed, and riffle particle size.

5.1. Reach attributes

The average values of discharge for baseflow of the more forested streams were higher than those of the less-forested streams (Table 3), which contradicts assumptions that forest removal increases water yield (Dunne and Leopold, 1978; Bosch and Hewlett, 1982; Sahin and Hall, 1996; Wohl, 2000; Jones and Post, 2004). The measured relationships of near-bankfull discharge were inconsistent between stream pairs. In one pair, the stormflow discharge of the moderately impacted stream (Skeenah Creek; 3.23 m^3/s) exceeds the lightly impacted stream (Coweeta Creek; 2.66 m^3/s). In the other pair, however, the stormflow discharge of the moderately impacted stream (Rocky Branch; 0.79 m^3/s) remained lower than that of the lightly impacted stream (Keener Creek; $1.90\,m^3/s$). Estimates of bankfull discharge using Manning's equation indicate higher values for both lightly impacted streams compared with the more moderately impacted counterparts (4.95 vs. $4.12\,m^3/s$ and 2.84 vs. $1.04\,m^3/s$).

Reach valley and floodplain morphology are inconsistent among the pairs (Table 3). Whereas lightly impacted Coweeta Creek has a wider average width of the meander belt than moderately impacted Skeenah Creek (34.55 vs. 11.57 m) and higher meander belt/channel width ratio (4.86 vs. 1.84), the opposite

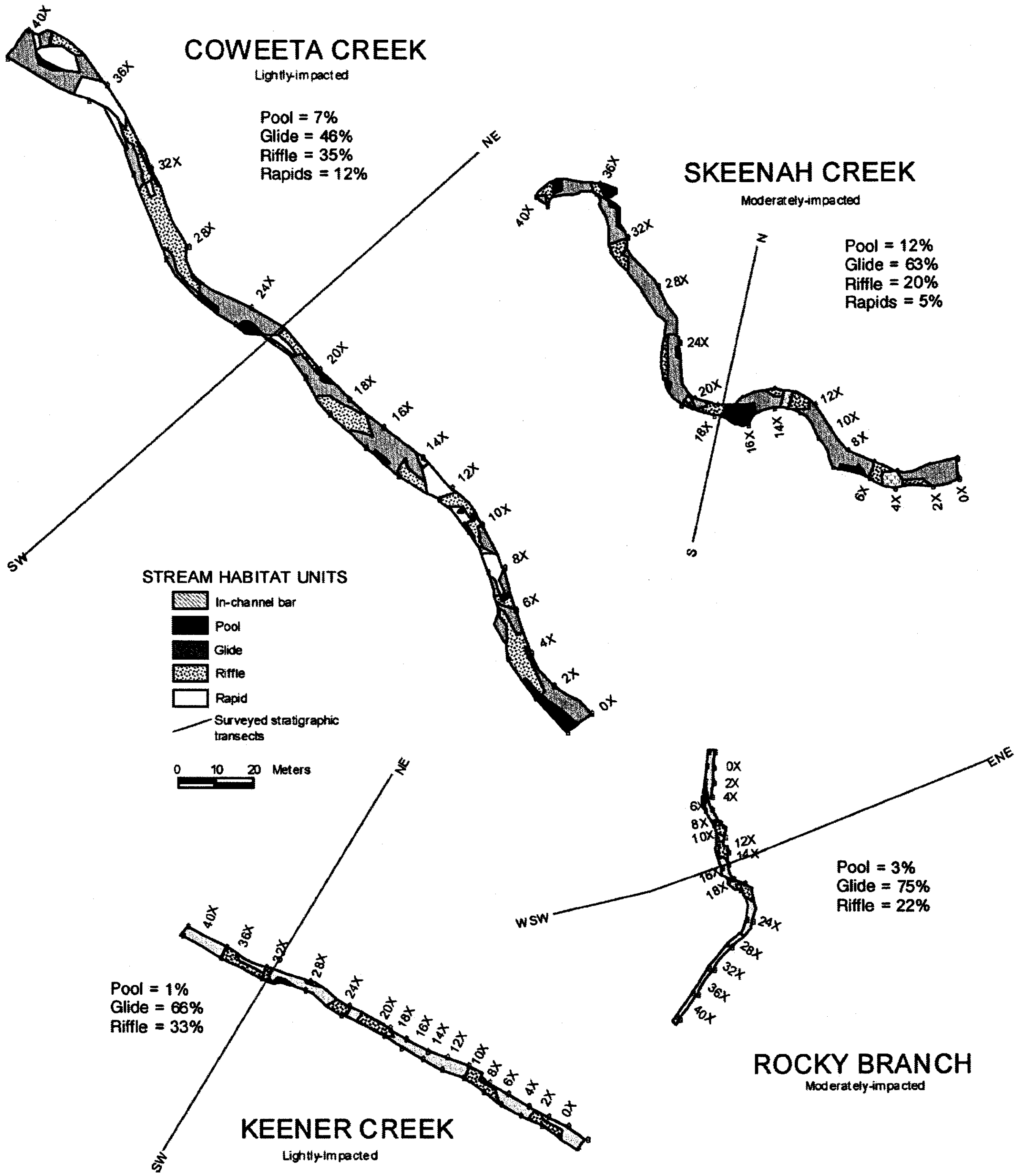

Fig. 4. Stream reach habitat units. Areal coverage of habitat units was hand-mapped using U.S. EPA habitat classes (Kaufmann and Robison, 1998) and digitized using ArcView® 3.2.

relationship is evident in the other pair. In lightly impacted Keener Creek, the width of the meander belt is lower than that of moderately impacted Rocky Branch (5.95 vs. 8.75 m), as is the meander belt/channel width ratio (1.30 vs. 3.92). Of the 32 banks measured along the transects, the streams with the more extensive meander belt from each pair (Coweeta Creek and Rocky Branch) have fewer terraced banks (three and two, respectively) than Skeenah Creek (18) and Keener Creek (22). Of the 16 cross-sections per stream, all transects of Coweeta Creek and Rocky Branch contained floodplain on at least one side of the stream, whereas Skeenah and Keener Creeks had floodplain on at least one side of the stream on 13 and 9 cross-sections, respectively (3 and 7 terraced cross-sections, respectively).

Glide is the dominant habitat unit of all four stream reaches (Fig. 4; Table 3), but all four streams have areas of pool, glide, and riffle. Additionally, Coweeta and

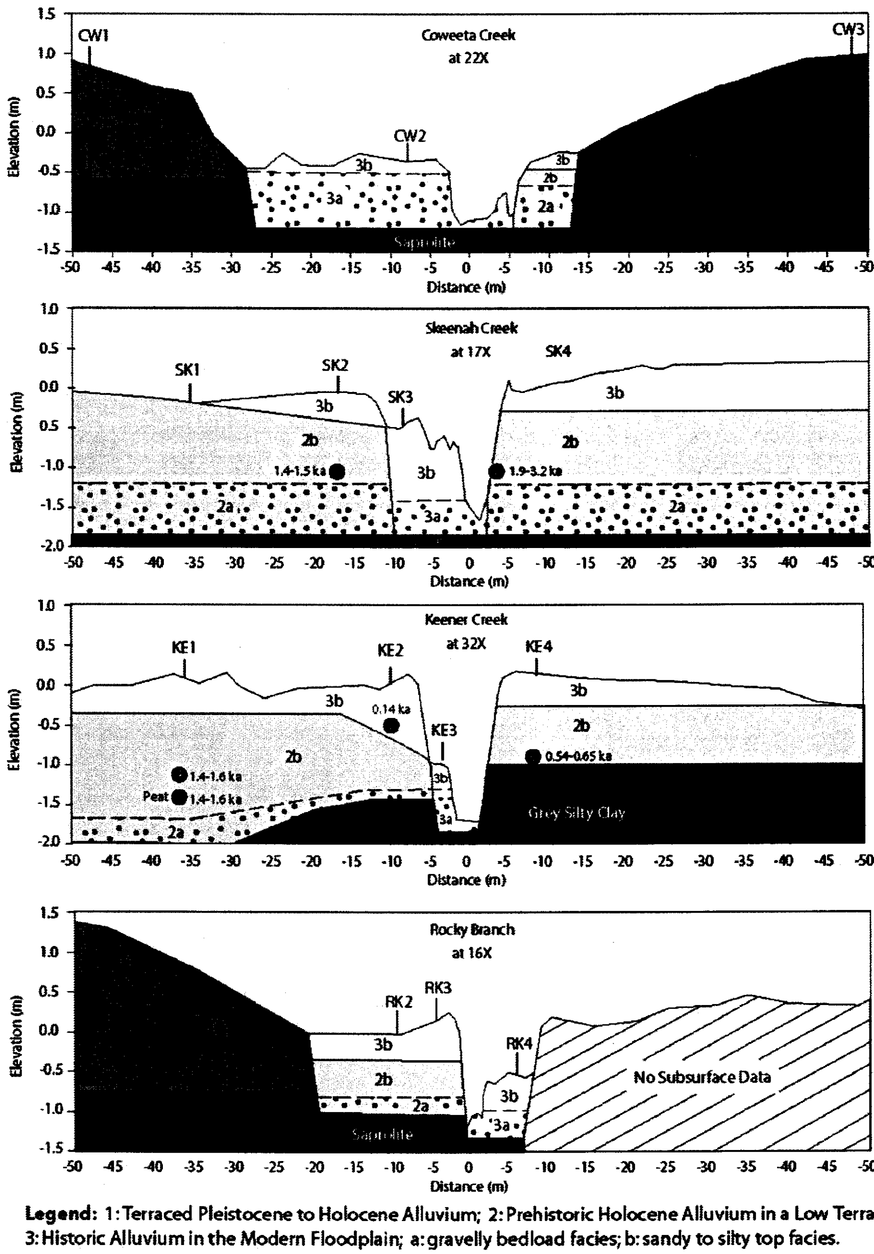

Fig. 5. Stratigraphic cross sections of study sites. Surface labels (i.e. RK2) indicate core hole locations. Radiocarbon samples are indicated by black circles in thousands of calendar years before present (ka). Corresponding laboratory numbers are (1) UGA#13068, (2) UGA#13067, (3) UGA#14483, (4) UGA#14484, (5) UGA#14485, and (6) UGA#14482.

Skeenah creeks contain small areas of rapids. By both measurements of habitat coverage (mapped percentage of surface area and percentage of sample points), the moderately impacted streams have lower riffle coverage and higher glide and pool coverage than the lightly impacted streams.

The dominant class of phi sizes of the bed particles in the lightly impacted streams is coarser than that of the moderately impacted streams (Table 3). A greater percentage of fines is evident in all metrics of the <2 mm fraction in moderately impacted Skeenah Creek than in lightly impacted Coweeta Creek. This relationship is generally true for the smaller pair, with the exception being the <2 mm fraction of the measurements for the random points survey of individual particles, which is lower in Rocky Branch than in Keener Creek.

5.2. Stratigraphic setting

The stratigraphic setting of all four sites is that of historical floodplain deposits laterally bounded by prehistoric terrace deposits (Fig. 5). Three chronostratigraphic units are recognized including: (1) terraced Pleistocene to Holocene alluvium, (2) prehistoric Holocene alluvium in a low terrace, and (3) historic alluvium in the modern floodplain. Radiocarbon dates confirm the chronostratigraphic designations. All three units are composed of graded sequences of bedload gravels that fine upward to sand, silt, and silt loam, but are distinguished by pedological traits and bounding surfaces. The oldest Unit 1 exhibits a well-expressed Bw horizon to incipient Bt horizon, whereas Unit 2 typically exhibits a youthful Bw horizon, and Unit 3 lacks B horizon development and commonly consists of unweathered stratified and laminated beds. Buried A horizons commonly are present in the top of Unit 2 and beneath the vertical accretion top-facies of Unit 3, clearly distinguishing the boundary between those units. The historical drape of Unit 3b on top of Unit 2 is comparable at all four sites, and no apparent excess of historical sediment occurs at the most impacted sites compared with the least impacted. The bedload facies of historical Unit 3 generally are at about the same elevation as the prehistoric bedload facies of Unit 2, indicating that these streams have not incised or degraded the beds significantly during historical time.

5.3. Dimensions of channels

Descriptive statistics of the dimensions of channels (Table 5) generally indicate either broad similarities or

Table 5
Cross-section descriptive statistics

		Coweeta (L)	Skeenah (M)	Keener (L)	Rocky (M)
A. Bank characteristics		*(n = 32 per stream)*			
Bank height (m)	mean	1.03	1.57	1.44	0.64
	std. dev.	0.21	0.32	0.57	0.23
	range	0.90	1.31	1.83	1.24
Bank angle (°)	mean	46	55	51	68
	std. dev.	28	33	18	21
	range	125	123	70	98
Bank stability index	mean	11.6	12.3	11.8	11.8
	std. dev.	1.7	1.6	1.2	1.0
	range	6.5	6.5	5.0	5.0
B. Channel-full dimensions[a]—all transects		(n = 16 per stream)			
Width (m)	mean	7.58	6.88	4.76	2.42
	std. dev.	2.27	1.87	1.43	0.68
	range	9.25	7.19	5.58	2.34
Depth to thalweg (m)	mean	1.01	1.36	1.17	0.60
	std. dev.	0.15	0.32	0.59	0.10
	range	0.54	0.98	1.59	0.29
Depth to water surface (m)	mean	0.59	0.95	0.89	0.32
	std. dev.	0.16	0.37	0.61	0.10
	range	0.57	1.16	1.64	0.43
Width/depth ratio (depth to thalweg)	mean	7.61	5.10	4.81	4.12
	std. dev.	2.52	1.07	1.85	1.35
	range	10.16	3.41	6.27	4.94
Width/depth ratio (depth to water surface)	mean	13.66	7.96	7.98	8.33
	std. dev.	5.37	2.69	5.10	3.55
	range	18.08	11.38	19.33	13.40
C. Bankfull dimensions[b]		(n = 6)	(n = 13)	(n = 9)	(n = 16)
Width (m)	mean	7.58	6.34	3.94	2.42
	std. rev.	2.27	1.51	0.57	0.68
	range	9.25	4.54	1.63	2.34
Depth to thalweg (m)	mean	1.01	1.23	0.69	0.60
	std. rev.	0.15	0.29	0.19	0.10
	range	0.54	0.98	0.67	0.29
Depth to water surface (m)	mean	0.59	0.85	0.40	0.32
	std. rev.	0.16	0.33	0.18	0.10
	range	0.57	1.16	0.66	0.43
Width/depth ratio (depth to thalweg)	mean	7.61	5.06	6.04	4.12
	std. rev.	2.52	1.12	1.47	1.35
	range	10.16	3.41	4.29	4.94
Width/depth ratio (depth to water surface)	mean	13.66	8.24	11.26	8.33
	std. rev.	5.37	2.87	4.57	3.55
	range	18.08	11.38	16.29	3.55
Floodplain width (m)	mean	13.49	2.35	0.59	3.16
	std. rev.	9.58	3.58	0.99	2.28
	range	37.00	12.80	3.09	9.00

L = lightly impacted; M = moderately impacted.

[a] Bank top.

[b] Bankfull measured where floodplain surfaces existed on either side of the stream.

Table 6
Difference of means test statistics

	Coweeta/Skeenah (L/M)	Keener/Rocky (L/M)
A. Bank, channel-full, and bankfull dimensions		
Bank angle		
n=32	T=964	T=786.5***
Bank stability index		
n=32	T=890**	T=1032
Channel-full width		
n=16	t=0.955	t=5.895***
Channel-full width/depth ratio (depth to thalweg)		
n=6	t=3.666***	t=1.198
Bankfull width (m)	t=1.691	t=5.697***
n=varied	n: Coweeta=16; Skeenah=13	n: Keener=9; Rocky=16
Bankfull width/depth ratio (depth to thalweg)	t=3.998***	t=3.490***
n=varied	n: Coweeta=16; Skeenah=13	n: Keener=9; Rocky=16
Bankfull width/depth ratio (depth to water surface)	T=114.0***	T=152.0
n=varied	n: Coweeta=16; Skeenah=13	n: Keener=9; Rocky=16
B. Baseflow channel dimensions		
Wetted width		
n=16	t=2.919**	t=7.917***
Average water depth (transects)		
n=16	t=−0.083	t=−2.852**
Baseflow width/depth ratio		
n=16	t=1.957	t=6.025***
Water depth at random points		
n=81	t=−1.702	t=−3.270***
Velocity at random points		
n=81	t=2.164*	t=0.631
Velocity in thalweg		
n=81	T=8712.5***	T=7.285*
Froude number at random points		
n=81	t=2.065*	t=1.873
Froude number in thalweg		
n=81	t=5.88***	t=2.266*
C. Sedimentology		
Individual particle measurements (mm)		
n=81	T=7354.5*	T=7205.5*
Individual particle measurements (ϕ)[a]		
n=81	T=5848.5*	T=5995*
Riffle particle size (mm)		
n=100	T=11375.5***	T=13474.5***
Riffle particle size (ϕ)[a]		
n=100	T=8709***	T=6619.5***
Dominant phi class random points (interval data)		
n=81	T=5629.5***	T=5698.5**
Dominant phi class in thalweg (interval data)		
n=81	T=4769.5***	T=5493***

L=lightly impacted; M=moderately impacted.
t=parametric t-test; T=Mann-Whitney Rank Sum non-parametric difference of means test.
*p<0.05; **p<0.01; ***p<0.001.
[a] ϕ units were derived from individuals particle measurements (mm).

inconsistent directions of differences between the pairs. Difference of means tests was run for those parameters for which the direction of difference between the lightly and moderately impacted streams was consistent in both pairs (Table 6). These tests indicate that only the bankfull width/depth (to thalweg) ratio and wetted width of the baseflow were significantly different in both pairs at the $p<0.01$ level.

Characteristics of the banks did not appreciably differ between lightly and moderately impacted streams (Table 5A). No pattern emerged between level of impact and bank height, and although the mean angles of the banks of the moderately impacted streams were higher than the lightly impacted streams in both pairs, the difference was not statistically significant between the larger streams (Table 6A). The indices of bank stability are roughly equal across all four streams, and all classify as "unstable" under Fitzpatrick et al.'s (1998) scheme.

Measurements for channel dimensions were analyzed using two separate approaches. Descriptive statistics were generated for all 16 transects per stream (channel-full dimensions; Table 5B), and summary values were generated for those transects with active floodplain on either or both sides (bankfull dimensions; Table 5C). By both methods, the depths to the thalweg and to the water surface showed inconsistent direction of difference between the lightly and moderately impacted streams. Although mean width of the channel-full and width/depth of the full channel (to thalweg) ratios are higher in the lightly impacted streams, these differences are not statistically significant. The bankfull widths and both variants of width/depth ratio are higher in the lightly impacted streams, but not all of these differences are statistically significant. Only the bankfull width/depth ratio (to thalweg) differences are statistically significant in both pairs (Table 6A), with the lightly impacted streams demonstrating higher bankfull width/depth ratios than the moderately impacted counterparts.

Table 7
Sedimentology descriptive statistics

		Coweeta (L)	Skeenah (M)	Keener (L)	Rocky (M)
Dominant phi class in thalweg* (interval data)	mean	−6.3	−3.7	−4.8	−4.6
	std. dev.	1.4	2.9	1.6	1.1
	range	12.0	13.0	13.0	7.0
Dominant phi class at random points* (interval data)	mean	−5.1	−3.7	−4.1	−3.6
	std. dev.	2.5	2.9	2.1	1.7
	range	9.0	12.0	13.0	7.0
Individual particle size at random points* (mm)	mean	64	42	32	21
	std. dev.	65	49	46	28
	range	37	210	375	224
Individual particle size at random points*,[a] (ϕ)	mean	−4.6	−3.5	−3.7	−3.5
	std. dev.	2.7	3.1	2.6	1.8
	range	8.6	12.2	13.1	7.8
Riffle particle size** (mm)	mean	61	45	35	9
	std. dev.	51	51	28	8
	range	290	215	146	34
Riffle particle size**,[a] (ϕ)	mean	−5.1	−3.4	−4.5	−2.3
	std. dev.	2.4	3.9	1.7	1.7
	range	12.7	12.2	7.2	5.1
Riffle fraction of random points survey*** (mm)	mean	90.4	64.7	34.0	30.4
	std. dev.	77.1	47.3	27.3	18.2
	range	373.0	166.0	120.0	71.0

L = lightly impacted; M = moderately impacted.
*n = 81 per stream; **n = 100 per stream; ***n = 19–35.
See Section 4.2.4 and Table 4 for descriptions of sedimentology data collection methods.
[a] ϕ units were derived from individual particle measurements (mm).

Statistical significance of differences possibly suffered because of the reduced sample size resulting from culling the terraced transects from Keener Creek and Skeenah Creek.

The only parameter of baseflow that is significantly different between the lightly and moderately impacted streams in both pairs is wetted width, which is greater in the lightly impacted streams (Table 6B). The means of average cross-sectional and random points water depth are lower in the lightly impacted streams than in the moderately impacted counterparts, but these means are not significantly different (Table 6). Mean depth of the thalweg shows no consistent direction of difference. Velocity and Froude number means from surveys of the thalweg and random points are higher in the lightly impacted streams, but these differences are not significant at the $p < 0.01$ level for both pairs.

5.4. Sedimentology

Dominant phi means from the random and thalweg longitudinal surveys indicate significantly smaller particle sizes in the moderately impacted streams (Table 7). The means of individual particle distributions from the random survey (in mm and Φ units) are smaller in the moderately impacted streams as well, but these differences are only significant at the $p < 0.05$ level, as opposed to $p < 0.01$ (Table 6C). The Wolman riffle pebble counts demonstrate a significantly finer size of riffle particles in the moderately impacted streams, and these streams have a higher percentage of riffle fines (Table 3). The differences in mean size of riffle particles, as determined by the riffles drawn from the random points and thalweg longitudinal surveys, are not statistically significant. As the moderately impacted streams have lower proportions of riffles than the lightly impacted streams, statistical significance of differences may have suffered from the low sample size that resulted from isolating the measurements of riffle particle sizes from the random and longitudinal surveys.

6. Discussion

This study shows that human impact in these basins has resulted in an overall fining of bed texture, but few conclusions can be drawn regarding morphological responses of the streams to the levels of impact affecting the upper Little Tennessee River basin. The majority of the morphological parameters measured in this study either failed to demonstrate significant differences at the 0.01 probability level between lightly and moderately impacted streams in both pairs, or exhibited inconsistent direction of difference among the pairs. Although widening of channels in response to intensive agriculture and urbanization has been well documented throughout the world, the modest differences in forest cover between these lightly and moderately impacted basins (90–100% vs. 70–80%) yield few statistically significant differences in morphological parameters. These data demonstrate that the moderately impacted streams are narrower than the lightly impacted streams. The lightly and moderately impacted streams in this study exhibited significant differences in dominant phi in the thalweg and entire channel bed, riffle particle size, baseflow wetted width, and bankfull width/depth (to thalweg) ratio. Unfortunately, very few data exist for streams in the southern Blue Ridge for comparison with these results.

6.1. Sedimentology and habitat distribution

Differences in sedimentology of the stream bed were much more readily apparent than were differences in channel morphology. All sedimentology metrics differed between lightly and moderately impacted streams, though measurements of individual particles from the random points survey were only significant at the $p<0.05$ level, rather than the $p<0.01$ threshold we established for designation of statistical significance. The pebble counts on riffles showed a significantly finer mean size of particles and higher percentages of <2 mm particles in the moderately impacted streams. The riffle-specific Wolman pebble count produced clearer results than isolating the riffle fraction of the total-bed random points survey, likely because sub-setting the streambed points into categories of habitat unit resulted in too small of a sample. This reaffirms that stratifying pebble counts by habitat units prior to data collection, as originally described by Wolman (1954) and advocated by Kondolf et al. (2003), is indeed a superior approach to generalizing the entire stream bed and later sub-setting particle sizes by habitat unit. In many highland pool-riffle systems, the riffles are the most clearly bounded and most easily identified unit of the stream. Of the commonly used units, riffles have been shown to be the most highly sensitive to external disturbance in the southern Appalachian Highlands. Roy et al. (2003a) found increases in fine sediment in riffles to be symptomatic of anthropogenic disturbance in the basin, and fine sediment-impacted riffles were associated with decreases in the richness of macroinvertebrate taxa.

The differences in the mean of the dominant particle size from the random and thalweg surveys were highly significant between the lightly and moderately impacted streams in both pairs. Whereas questions of repeatability surround methods of visual assessment for categorical data of particle size (Kondolf et al., 2003), the estimation of dominant phi size class may provide more information regarding the availability of aquatic habitat within the channel than randomly selected individual particles. In this study, the mean of the dominant particle size was a successful indicator of basin disturbance and did not drastically differ from the random points survey of individual particle diameters. In cases where visual assessment of dominant particle size is desired, we recommend using standard Wentworth-scale phi size classes, to allow for comparison of results with assessment of particle size from other methods. Such an approach was also proven to be highly successful in characterizing the suitability of habitat in a stream for specific types of fish assemblages (Walters et al., 2003a,b).

Data for suspended sediment support the trend suggested by the data for bed sedimentology that human impact in these basins is increasing the input of fine sediment into streams. The means of total suspended solids (TSS) in the baseflow of the moderately impacted stream were approximately triple that of the lightly impacted stream within both pairs (Skeenah and Coweeta Creeks: 7 vs. 2 mg/L; Rocky Branch and Keener Creek: 14 vs. 4 mg/L; $n=12$). Most of this difference was accounted for by suspended mineral sediment, rather than organic solids (Price and Leigh, in press). TSS differences between the lightly and moderately impacted streams were even more pronounced during the near-bankfull flood, with TSS of the moderately impacted streams substantially larger than that of the lightly impacted streams within both pairs (829 vs. 68 mg/L and 456 vs. 149 mg/L; Price and Leigh, in press). Using turbidity as a proxy for suspended sediment concentration, Sutherland et al. (2002) observed mean values for turbidity of 3.6 and 3.8 NTU for upper Little Tennessee River sub-basins that were 99% and 97% forested, respectively, whereas the mean values for turbidity of streams draining 87% and 78% forested basins were much higher (15.0 and 14.6 NTU). Assuming the principal sources of higher suspended sediment yield to be from the drainage basin and/or stream banks, higher values of suspended sediment would be expected to correspond with a decreasing size of bed particles, as has been observed in Little Tennessee River tributaries. This correspondence of higher values of suspended sediment and finer bed texture in the moderately impacted streams suggests that fining does not result from reduced input of coarse particles. Increased input of fine sediment to stream systems associated with late 20th century development has been demonstrated elsewhere in the region (e.g., Miller et al., 2003). No indications exist that the fining of stream beds results from decreased delivery of coarse sediment.

Although infilling of pools with fine particles has been indicated as symptomatic of disturbance in other highland regions of the United States (Lisle, 1982; Wohl et al., 1993; Madej and Ozaki, 1996; Wohl, 2000), this approach may not be applicable in the highly weathered southern Appalachians, because of the natural prevalence of fines in watersheds. The thick saprolite in this region serves as an abundant supply of fine sediment, which tends to accumulate in the lower velocity areas of streams, such as channel margins and pools. Riffles, however, remain dominated by coarse clasts in the absence of human impact. Increases in sediment supply to southern Appalachian Highland stream systems apparently lead to a decrease in particle size in riffles, though not necessarily in pools, which are likely to have been predominantly fine-textured prior to any disturbance. These data suggest that increases in sediment yield may be expanding the areal extent of pool and glide space, thereby decreasing the overall size of bed particles of Blue Ridge streams. This trend is opposite that observed in other regions, where pool space has been observed to decrease with sediment input from human impact (Wohl, 2000). Again, the small sample size in this study precludes widespread regional generalization. The abundant fine sediment in the saprolite-draped southern Blue Ridge may result in responses in streams that contrast with trends observed in characteristically coarser highlands in the western United States.

Variations in reach slope have been associated with differences in the distribution of habitat units in streams (Wohl et al., 1993). Differences in reach slope in the stream pairs in this study are not great enough to cast doubt on the role of increased sediment input because of basin land use. In the southernmost Blue Ridge and adjacent Piedmont, Leigh et al. (2002) demonstrated that basin land use explained the distribution of habitat units across a wide range of reach slopes in 32 streams. Vogt (2004) demonstrated that basin land use explained more variability in distribution of habitat in 11 streams in the southern Blue Ridge than did reach slope, and found decreased riffle coverage and increased glide space to be associated with forest conversion.

6.2. Dimensions of channels

The mean wetted width of baseflow was significantly greater in the lightly impacted streams. This difference is explained by the higher values of baseflow discharge in the lightly impacted streams, especially considering that mean values for water depth are not significantly different. Despite similar drainage areas, the lower baseflow discharge of the more-forested streams implies that the widely accepted predictions that the removal of forest results in increased water yield in response to decreased evapotranspiration may only apply to mean annual flow or similarly general metrics of discharge. The mean bankfull width/depth ratio (depth to thalweg) and mean wetted width of baseflow of both of the lightly impacted streams were significantly higher than those of the moderately impacted streams. One possible explanation for lower width/depth ratios in the moderately impacted streams is that greater sediment yield from erosive land use in these basins is accreting on the stream banks and floodplains. The specific land uses in these basins are not resulting in increased storm runoff to the extent necessary for the observed enlargement of channels in regions of intense agricultural and urban land use. Greater historical vertical accretion in the moderately impacted streams is evident in the valley stratigraphy (Fig. 5).

6.3. Discharge

Although the estimated bankfull discharge using Manning's equation is higher in the lightly impacted streams than the moderately impacted streams, the measured values of discharge from the February 6, 2004 frontal storm indicated that slightly higher levels of runoff are affecting moderately impacted Skeenah Creek compared to lightly impacted Coweeta Creek. The runoff of these two streams were sampled within 45 min of each other during the rising limb of the frontal storm, and the spatial proximity allows confidence that similar levels of precipitation affected both basins (study reaches are only 5.6 km apart). The measured stormflow discharge of moderately impacted Rocky Branch, however, remained lower than that of Keener Creek, which may indicate that the types of disturbance affecting the Rocky Branch basin are not resulting in higher levels of surface runoff. The stormflow discharges of these two streams were also measured within a 45-min interval, but the basins are not as close together as those of Skeenah Creek and Coweeta Creek (study reaches of Keener Creek and Rocky Branch are 31.8 km apart), and it is possible that the amount of precipitation was not precisely equal in time or space between this smaller pair of basins. A further possibility is that differences in basin morphology result in pronounced differences in rate of stormwater removal from the basins. Unlike Rocky Branch, Keener Creek has remarkably steep headwaters, perhaps resulting in greater flow during the rising limb of runoff.

6.4. Overview

More pronounced differences in sedimentology than morphology in these basin pairs suggest that bed sedimentology is more sensitive to disturbance and responds more quickly to changes in the basin than channel form. Also, the lack of morphological differences in this study may indicate that assessment of the reach scale (40× or shorter) of a small number of streams is not sufficient to capture system-wide morphological responses to human impact. It is possible that differences in channel morphology are more variable in space and time than sedimentology, thus requiring more extensive sampling to document. Indeed, Schumm (1973) indicates that because of the complexity of the fluvial system, it is not always possible to clearly identify morphological response to disturbance. Nagle and Clifton (2003) indicated lag times in morphological response to external changes as a possible explanation for an absence of differences between the morphology of streams pre- and post-exclusion of cattle. Miller et al. (1993) demonstrated the morphological responses of lag times of many decades in southern Illinois. The morphology of the streams assessed in this study may not have adjusted to disturbances in the late-20th century.

Another possibility is that the lightly impacted basins never fully recovered to baseline conditions that existed prior to timber harvest pre-dating federal protection, which began in 1911. In northern California, morphological adjustments to timber harvest have been shown to persist more than 100 years (Napolitano, 1998). The valley stratigraphy of these sites, however, indicates this is not likely the case for these streams. The stratigraphic settings of the sites failed to reveal any clear differences that distinguish the most- from least-impacted basins (Fig. 5). All four sites appear to be in the final stage of channel and floodplain evolution indicated by Jacobson and Coleman (1986) for Piedmont streams that experienced pronounced sediment loading during the late 19th and early 20th centuries. The streams have accomplished moderate levels of lateral migration and construction of floodplains, rather than being entrenched channels confined by large amounts of top facies on the banks and valley floor. This may indicate that all four streams have "recovered" to comparable levels since the time of most widespread forest harvest that occurred circa 75–150 years ago. Furthermore, these results indicate that significant amounts of incision or aggradation of the stream bed cannot be detected in these upper Little Tennessee River tributaries in response to differing levels of human impact. The relative elevation of streambed gravels of the historic versus late prehistoric units are within 23–30 cm of each other, which is well within the expected range of variation in the modern stream bed. Based on the limited sample of one cross-section at each stream, with only four stratigraphic sections, and with such minor variation in the heights of gravels, we see no conclusive evidence of aggradation or degradation for the four sampled sites.

Many common assessment methods for streams call for collection of data for a wide variety of sedimentological and morphological parameters (e.g., U.S. EPA-EMAP and USGS-NAWQA). These approaches are time consuming and perhaps unnecessary for certain objectives (Nagle and Clifton, 2003). The literature does not clearly validate collection of a thorough suite of morphological parameters at the reach scale, and it may be more efficient and advantageous for stream monitoring methods to focus on those parameters repeatedly demonstrated as sensitive to disturbance. This study has identified the sedimentology of the streambed as a key indicator, as others have (Jackson et al., 2001; Pruitt et al., 2001; Roy et al., 2003a,b; Walters et al., 2003a,b). Furthermore, sedimentology of the streambed is closely associated with biotic habitat of the stream. The measurement of fewer parameters at more cross sections has been shown to be superior to few, highly detailed cross-sections (Robison and Beschta, 1989). Studies have indicated that the morphology of baseflow, which is less subjective than bankfull morphology and more quickly assessed, can provide adequate information for certain objectives (Magilligan and McDowell, 1997; Nagle and Clifton, 2003). Thus, especially where time and efficiency are concerned, we advocate measurement of a limited set of quantitative characteristics of the stream bed, rather than bankfull characteristics, to detect incipient or emerging levels of human impact on streams and good relationships with biotic conditions.

7. Summary and conclusions

These results indicate that highland land use, involving modest changes in forest cover at the basin-scale, may cause significant differences in the sedimentology of stream beds. Morphological response to low levels of disturbance at the 40× reach scale of analysis, however, is not clear. Careful alignment of reach characteristics of stream pairs allowed for isolation of contrasting forest cover as the primary driver of sedimentological and morphological differences in streams. Streams draining the moderately impacted basins in this study (70–80% forest) demonstrate lower bankfull width/depth ratios, narrower wetted widths of baseflows, and finer texture of the stream bed. Whereas the sedimentology of these streams is clearly different, few conclusions can be drawn regarding morphological differences. Assessment of the reach-scale sedimentology of the stream bed, particularly that of riffles, was shown to be a successful scheme for identification of differences. Particle size and embeddedness on riffles have been shown to be linked with the biotic integrity of streams and to be highly sensitive to external disturbance in the southern Appalachian Highlands. Perhaps these parameters are among the best indicators of stream response to human impact. The levels of impact affecting the upper Little Tennessee River tributaries may be below the thresholds of morphological sensitivity or have not persisted long enough to induce response. Standard assessment methodologies at the reach-scale were followed for data collection. This study indicates that these methods, although appropriate for the assessment of the sedimentology of the stream bed, may not be optimal for assessment of morphological response to disturbance at the reach scale of analysis, particularly with few sample sites.

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References

Aust, W.M., 1994. Best management practices for forested wetlands in the southern Appalachian region. Water, Air and Soil Pollution 77 (3–4), 457–468.

Ayers, H.B., Ashe, W.W., 1904. The Southern Appalachian Forests. Professional Paper, vol. 37. U.S. Geological Survey.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55, 3–23.

Brooks, A.P., Brierley, G.J., 1997. Geomorphic responses of lower Bega River to catchment disturbance, 1851–1926. Geomorphology 18, 291–304.

Daniel III, C.C., Payne, R.A., 1990. Hydrogeologic unit map of the Piedmont and Blue Ridge provinces of North Carolina. Water-Resources Investigations Report, vol. 90-4035. U.S. Geological Survey, Raleigh, NC.

Delcourt, P.A., Delcourt, H.R., 2004. Prehistoric Native Americans and Ecological Change: Human Ecosystems in eastern North America since the Pleistocene. Cambridge University Press, Cambridge.

Delcourt, P.A., Delcourt, H.R., Cridlebaugh, P.A., Chapman, J., 1986. Holocene ethnobotanical and paleoecological record of human impact on vegetation in the Little Tennessee River Valley, Tennessee. Quaternary Research 25, 330–349.

Doyle, M.W., Harbor, J.M., Rich, C.F., Spacie, A., 2000. Examining the effects of urbanization on streams using indicators of geomorphic stability. Physical Geography 21 (2), 155–181.

Dunne, T., Leopold, L.B., 1978. Water in Environmental Planning. W. H. Freeman and Company, San Francisco.

Eaton, L.S., Morgan, B.A., Kochel, R.C., Howard, A.D., 2003. Role of debris flows in long-term landscape denudation in the central Appalachians of Virginia. Geology 31 (4), 339–342.

Fitzpatrick, F.A., Waite, I.R., D'Arconte, P.J., Meador, M.R., Maupin, M.A., Gurtz, M.E., 1998. Revised methods for characterizing stream habitat in the national water-quality assessment program. Water-Resources Investigations Report, vol. 98-4052. U.S. Geological Survey, Raleigh, NC.

Fortino, K., Hershey, A.E., Goodman, K.J., 2004. Utility of biological monitoring for detection of timber harvest effects on streams and evaluation of best management practices: a review. Journal of the North American Benthological Society 23 (3), 634–646.

Hadley, J.B., Goldsmith, R., 1963. Geology of the eastern Great Smoky Mountains, North Carolina and Tennessee. Professional Paper, vol. 349-B. U.S. Geological Survey.

Hartman, G.F., Scrivener, J.C., Miles, M.J., 1996. Impacts of logging in Carnation Creek, a high-energy coastal stream in British Columbia, and their implication for restoring fish habitat. Canadian Journal of Fisheries and Aquatic Sciences 53 (Supplement 1), 237–251.

Heede, B.H., 1991. Response of a stream in disequilibrium to timber harvest. Environmental Management 15, 251–255.

Jackson, C.R., Sturm, C.A., Ward, J.M., 2001. Timber harvest impacts on small headwater stream channels in the coast ranges of Washington. Journal of the American Water Resources Association 37 (6), 1533–1549.

Jacobson, R.B., Coleman, D.J., 1986. Stratigraphy and recent evolution of Maryland Piedmont flood plains. American Journal of Science 286, 617–637.

Johnson, M.G., Beschta, R.L., 1980. Logging, infiltration, and surface erodibility in western Oregon. Journal of Forestry 78, 334–337.

Jones, J.A., Post, D.A., 2004. Seasonal and successional streamflow response to forest cutting and regrowth in the northwestern and eastern United States. Water Resources Research 40, 1–19.

Kaufmann, P.R., Robison, E.G., 1998. Field Operations and Methods for Measuring the Ecological Condition of Wadeable Streams, Section 7: Physical habitat characterization PA/620/R-94/004F. U.S. Environmental Protection Agency, Research Triangle Park, NC.

Kennan, J.G., Ayers, M.A., 2002. Relation of environmental characteristics to the composition of aquatic assemblages along a gradient of urban land use in New Jersey, 1996–1998. Water-Resources Investigations Report, vol. 02-4069. U.S. Geological Survey, West Trenton, NJ.

Knighton, D., 1998. Fluvial Forms and Processes: A New Perspective. Edward Arnold, London.

Knox, J.C., 1987. Historical valley floor sedimentation in the Upper Mississippi Valley. Annals of the Association of American Geographers 77 (2), 224–244.

Kondolf, G.M., Lisle, T.E., Wolman, M.G., 2003. Bed sediment measurement. In: Kondolf, G.M., Piegay, H. (Eds.), Tools in Fluvial Geomorphology. Wiley, West Sussex, pp. 347–396.

Leigh, D.S., Walters, D.M., Roy, A.H., Freeman, B.J., Freeman, M.C., Kramer, E.A., Paul, M.J., Pringle, C.M., Rosemond, A.D., 2002. Landscape Indicators of Biotic Integrity in Piedmont Streams of the Etowah Basin, North Georgia, U.S.A. Final Technical Report Submitted to the United States Environmental Protection Agency to Fulfill Requirements of a Science to Achieve Results (STAR) Grant (#R826597-01-0). Research Report 2, The University of Georgia Geomorphology Laboratory, Athens, GA.

Lisle, T.E., 1982. Effects of aggradation and degradation on riffle-pool morphology in natural gravel channels, northwestern California. Water Resources Research 18, 1643–1651.

Madej, M.A., Ozaki, V., 1996. Channel response to sediment wave propogation and movement, Redwood Creek, California, USA. Earth Surface Processes and Landforms 21, 911–927.

Magilligan, M.J., McDowell, P.F., 1997. Stream channel adjustments following elimination of cattle grazing. Journal of the American Water Resources Association 33 (4), 867–878.

Miller, S.O., Ritter, D.F., Kochel, R.C., Miller, J.R., 1993. Fluvial responses to land-use changes and climatic variations within the Drury Creek watershed, southern Illinois. Geomorphology 6, 309–329.

Miller, J.R., Kolenbrander, L., Lord, M., Yurkovich, S., Mackin, G., 2003. Assessment of changing land-use practices on sediment yield and provenance in Western North Carolina using multivariate fingerprinting techniques. Report, vol. 345. Water Resources Research Institute of the University of North Carolina.

Montgomery, D.R., Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. GSA Bulletin 109 (5), 596–611.

Nagle, G.N., Clifton, C.F., 2003. Channel changes over 12 years on grazed and ungrazed reaches of Wickiup Creek in eastern Oregon. Physical Geography 24 (1), 77–95.

Napolitano, M.B., 1998. Persistence of historical logging impacts on channel form in mainstem North Fork Caspar Creek. Conference in Coastal Watersheds: The Caspar Creek Story. USDA Pacific Southwest Research Station, Albany, CA, pp. 97–101.

National Climate Data Center (NCDC), 2003. Climatography of the United States no. 84, 1971–2000.

Pope, B.F., Tasker, G.D., Robbins, J.C., 2001. Estimating the magnitude and frequency of floods in Rural Basins of North Carolina-revised. Water-Resources Investigations Report, vol. 01-4207. U.S. Geological Survey, Raleigh, NC.

Price, K., Leigh, D.S., in press. Comparative water quality of lightly and moderately impacted streams in the southern Blue Ridge Mountains, USA. Environmental Monitoring and Assessment.

Prud'homme, B.A., Greis, J.G., 2002. Best management practices in the south. In: Wear, D.N., Greis, J.G. (Eds.), Southern Resource Assessment. Southern Research Station, Forest Service. U.S. Department of Agriculture, Asheville, NC, pp. 519–535.

Pruitt, B.A., Melgaard, D.L., Howard, H., Flexner, M.C., Able, A. S., 2001. Chattooga river watershed ecological sedimentation project. Federal Inter-Agency Sedimentation Conference, vol. 7, pp. X89–X96.

Reid, L.M., Dunne, T., 1984. Sediment production from forest road surfaces. Water Resources Research 20, 1753–1761.

Robison, E.G., Beschta, R.L., 1989. Estimating stream cross sectional area from wetted and thalweg depth. Physical Geography 10, 190–194.

Robinson Jr., G.R., Lesure, F.G., Marlowe II, J.I., Foley, N.K., Clark, S.H., 1992. Bedrock geology and mineral resources of the Knoxville 1 degrees by 2 degrees quadrangle, Tennessee, North Carolina, and South Carolina. Bulletin, vol. 1979. U.S. Geological Survey, Reston, VA.

Roy, A.H., Rosemond, A.D., Leigh, D.S., Paul, M.J., Wallace, J.B., 2003a. Habitat-specific responses of macroinvertebrates to land cover disturbance: biological consequences and monitoring implications. Journal of the North American Benthological Society 22 (2), 293–307.

Roy, A.H., Rosemond, A.D., Paul, M.J., Leigh, D.S., Wallace, J.B., 2003b. Stream macroinvertebrate response to catchment urbanization (Georgia, U.S.A.). Freshwater Biology 48, 329–346.

Sah, M.P., Mazari, R.K., 1998. Anthropogenically accelerated mass movement, Kulu Valley, Himachel Pradesh, India. Geomorphology 26, 123–138.

Sahin, V., Hall, M.J., 1996. The affects of afforestation and deforestation on water yields. Journal of Hydrology 178, 293–309.

Schumm, S.A., 1973. Geomorphic thresholds and the complex response of river systems. In: Morisawa, M. (Ed.), Fluvial Geomorphology. Publications in Geomorphology. State University of New York, Binghamton, pp. 299–310.

Schumm, S.A., 1977. The Fluvial System. John Wiley and Sons, New York.

Soil Survey Division Staff, 1993. Soil Survey Manual. USDA Handbook, vol. 18. GPO, Washington, DC.

Southworth, S., Schultz, A., Denenny, D., Triplett, J., 2003. Surficial geologic map of the great smoky mountains National Park Region, Tennessee and North Carolina. Open File Report, vol. 03-081. U.S. Geological Survey.

Strahler, A.N., 1952. Hypsometric (area-altitude) analysis of erosional topography. Bulletin of the Geological Society of America 63, 1117–1142.

Stuiver, M., Reimer, P.J., 1993. Extended C-14 data-base and revised Calib 3.0 C-14 Age Calibration Program. Radiocarbon 35 (1), 215–230.

Sutherland, A.S., Meyer, J.L., Gardiner, E.P., 2002. Effects of land cover on sediment regime and fish assemblage structure in four southern Appalachian streams. Freshwater Biology 47, 1791–1805.

Trimble, S.W., 1981. Changes in sediment storage in the Coon Creek basin, Driftless Area, Wisconsin, 1853 to 1975. Science 214 (4517), 181–183.

Vogt, A.E., 2004. Responses in instream habitat and fishes to modest changes in forest cover in southeastern streams. M.S. Thesis, The University of Georgia, Athens, GA.

Walker, L.C., 1991. The Southern Forest. University of Texas Press, Austin, TX.

Walters, D.M., Leigh, D.S., Bearden, A.B., 2003a. Urbanization, sedimentation, and homogenization of fishes in the Etowah River basin, Georgia Piedmont, USA. Hydrobiologia 494, 5–10.

Walters, D.M., Leigh, D.S., Freeman, M.C., Freeman, B.J., Pringle, C.M., 2003b. Geomorphology and fish assemblages in a Piedmont river basin, U.S.A. Freshwater Biology 48, 1950–1970.

Wang, J.X., McNeel, J., Milauskas, S., 2004. Logging sediment control act and forestry best management practices in West Virginia: a review. Northern Journal of Applied Forestry 21 (2), 93–99.

Williams, G.P., 1978. Bank-full discharge of rivers. Water Resources Research 14 (6), 1141–1154.

Wohl, E., 2000. Mountain Rivers. Water Resources Monograph, vol. 14. American Geophysical Union, Washington, DC.

Wohl, E.E., Vincent, K.R., Merritts, D.J., 1993. Pool and riffle characteristics in relation to channel gradient. Geomorphology 6, 99–110.

Wolman, M.G., 1954. A method of sampling coarse river-bed material. Transactions of the American Geophysical Union 35 (6), 951–956.

Wolman, M.G., 1967. A cycle of sedimentation and erosion in urban river channels. Geografiska Annaler 49A (2–4), 385–395.

Wood-Smith, R.D., Buffington, J.M., 1996. Multivariate geomorphic analysis of forest streams: implications for assessment of land use impacts on channel condition. Earth Surface Processes and Landforms 21, 337–393.

Yarnell, S.L., 1998. The Southern Appalachians: a History of the Landscape. General Technical Report, vol. SRS-18. U.S. Department of Agriculture Forest Service Southern Research Station, Asheville, NC.